PL-TR-96-2273 SSS-DTR-96-15562

Regionalized Maximum Likelihood Surface Wave Analysis

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September 1996

Scientific Report No. 1

PHILLIPS LABORATORY
Directorate of Geophysics
AIR FORCE MATERIEL COMMAND
HANSCOM AFB, MA 01731-3010

SPONSORED BY
Air Force Technical Applications Center
Directorate of Nuclear Treaty Monitoring
Project Authorization T/5101

MONITORED BY
Phillips Laboratory
CONTRACT No. F19628-95-C-0110

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1996	Scientific Report No. 1

4. TITLE AND SUBTITLE

Regionalized Maximum Likelihood Surface Wave Analysis

5. FUNDING NUMBERS

F19628-95-C-0110
PE 35999F
PR 5101 TA GM WU AC

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Maxwell Technologies
8888 Balboa Avenue
San Diego, CA 92123-1506

8. PERFORMING ORGANIZATION REPORT NUMBER

SSS-DTR-96-15562

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Phillips Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010
Contract Manager: Delaine Reiter/GPE

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

PL-TR-96-2273

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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Automatic surface wave processing has been implemented at the Prototype International Data Center since May, 1995, using a program, Maxsurf, developed by Maxwell Technologies. We have developed a new program Maxpmf, based on Maxsurf, with the addition of a phase-matched filtering module, and used it to estimate moments in automatic processing mode from a large data set of waveforms recorded at the GSETT 3 primary stations (3-Component long

14. SUBJECT TERMS

Surface Waves Earthquake/Explosion Discrimination Ms
Rayleigh Waves Maximum Likelihood Moment

15. NUMBER OF PAGES
26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

CLASSIFIED BY:

DECLASSIFY ON:

13. Abstract (Continued)

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Maximum likelihood magnitudes were calculated for a data set of 174 events using amplitude levels from nondetections as measured noise levels. The results demonstrate the need for a high level of quality control if maximum likelihood magnitudes are to be meaningful. In particular, noise levels from nondetections must be measured as accurately as signals, and the results can be severely distorted by low amplitudes from stations that are not operating properly.

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Summary

We develop a method for regionalization of surface wave magnitudes, replacing the traditional M_s measurement with a new type of magnitude, the scalar moment, derived from the equations for surface waves from point sources in layered media. This has the effect of minimizing the frequency dependence and distance dependence of the magnitude, and allows worldwide regionalization so that the magnitude is a consistent measure of source size for any source and receiver location.

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Keywords: surface waves, Rayleigh waves, earthquake/explosion discrimination, M_s, moment, maximum likelihood

1. Introduction

The primary objective of this research program is to develop and test a transportable regional discriminant based on a maximum likelihood analysis of fundamental mode Rayleigh waves. This is to be accomplished by implementing and extending the method developed by Stevens and McLaughlin (1988). This method applies phase-matched filters to data, recovers spectra, flattens the spectrum with a frequency dependent amplitude correction, and recovers a spectral magnitude (scalar moment). This procedure is to be applied to a large data set and its range of applicability, limitations, and discrimination capability determined.

Specifically, we are looking for the following:

1. An accurate measure of surface wave amplitude, similar to M_s, that is independent of distance and frequency.
2. A mechanism for regionalizing the magnitude to account for regional differences in dispersion, attenuation, and excitation.
3. A method for determining an upper bound on the magnitude in cases where no surface wave is measurable.
4. A discriminant similar to m_b:M_s, but more robust, with a wider range of applicability and with the ability to use nondetections as well as measured amplitudes.
5. Automation of the surface wave identification and measurement process to the maximum extent possible.

2. Regionalized Surface Waves - Theory

In order to use a regionalized earth model to develop a consistent method for measuring Rayleigh waves, it is necessary to separate the surface wave into functions that depend on the source region, the source to receiver travel path, and the receiver region. The displacement spectrum for a Rayleigh wave at distance r from an *explosion* is given by:

$$U(\omega,r) = M_o' \frac{S_1^x(\omega,h_x) * S_2(\omega)\exp[-\gamma_2(\omega)r + i(\varphi_o - \omega r / c_2(\omega))]}{\sqrt{a_e}\sin(r/a_e)} \qquad (1)$$

S_1^x depends on the source region elastic structure and source depth.

S_2 depends on the receiver region elastic structure.

γ_2 (attenuation) depends on the path Q structure.

c_2 (phase velocity) depends on the path elastic structure.

φ_o is the initial phase of the source.

α_e is the radius of the earth.

$M_0^{'} = \frac{3\beta^2}{\alpha^2} M_0$ where M_o is the explosion isotropic moment where α and β are the compressional and shear wave speeds, respectively, at the explosion source depth. $M_0^{'}$ is the scalar moment, a measure of source size.

For an explosion or an earthquake, we define:

$$M_0^{'} = \left| U(\omega, r, \theta) \Big/ \frac{S_1^x(\omega, h_x) S_2(\omega) \exp[-\gamma_2(\omega) r + i(\varphi_o - \omega r / c_2(\omega))]}{\sqrt{a_e \sin(r / a_e)}} \right| \qquad (2)$$

For an explosion, $M_0^{'}$ is a constant independent of frequency. For an earthquake with double couple moment M_0:

$$M_0^{'} = M_0 \left| S_1^q(\omega, h_q, \theta) \Big/ S_1^x(\omega, h_x) \right| \qquad (3)$$

where S_1^q depends on the double couple orientation, depth takeoff azimuth, and source region elastic structure. $M_0^{'}$ is insensitive to local material properties and the only frequency dependence is the ratio of earthquake/explosion excitation functions defined above.

By defining the scalar moment this way, we obtain a measure of the surface wave magnitude that is independent of range, nearly independent of frequency, and regionalizeable. The functions S_1 and S_2 depend only on the source region structure near the source and receiver points and can be stored in a simple lookup table. The functions c_2 and γ_2 are functions of the path and can be found by integrating along the great circle path between the source and receiver in a regionalized earth model. The phase of the explosion Green's function can be used as a phase-matched filter to improve signal to noise ratio. The scalar moment can be determined by averaging over a frequency band, thereby avoiding dips and peaks in the spectrum. Furthermore, since the scalar moment is nearly independent of frequency, the average can be done in the frequency band with the highest signal to noise ratio, and results will be consistent even if different frequency bands are used for different regions and different data sets.

3. Rayleigh Wave Identification and Measurement

We have developed an automatic surface wave processing/phase-matched filtering program and applied it to a large data set at the Prototype International Data Center in Arlington, VA. The program, Maxpmf, is based on the automated processing program Maxsurf with the addition of a phase-matched filtering/moment estimation module. Maxsurf, developed by Maxwell Technologies, is used to identify and measure all surface waves that appear in the IDC bulletin.

3.1 Automatic Surface Wave Processing

Surface wave identification is accomplished in the following way: for each origin identified through short period arrivals, the data in the surface wave arrival time window (approximately 5 km/sec to 2 km/sec) is extracted and the following tests are performed:

1. A set of narrow-band filters are applied to determine the group velocity dispersion as a function of frequency.
2. The observed dispersion is compared with the predicted dispersion based on ray tracing along a great circle path through a regionalized earth model. As shown in Figure 1, the observed dispersion data points are required to fall within a specified range of the predicted dispersion curves. One or two points may be allowed to fall outside this range to allow for cases when noise contamination or interference causes some part of the measured dispersion to be inconsistent with the rest of the dispersion curve.
3. The azimuth to the origin is estimated based on polarization filtering for three-component data, and best beam azimuth for long period array data.
4. If these tests show the characteristics of a surface wave then an arrival is added to the bulletin. The amplitude is measured by digitally replacing the instrument with a KS36000 long period instrument and measuring the amplitude of the arrival near 20 seconds period in the time domain.

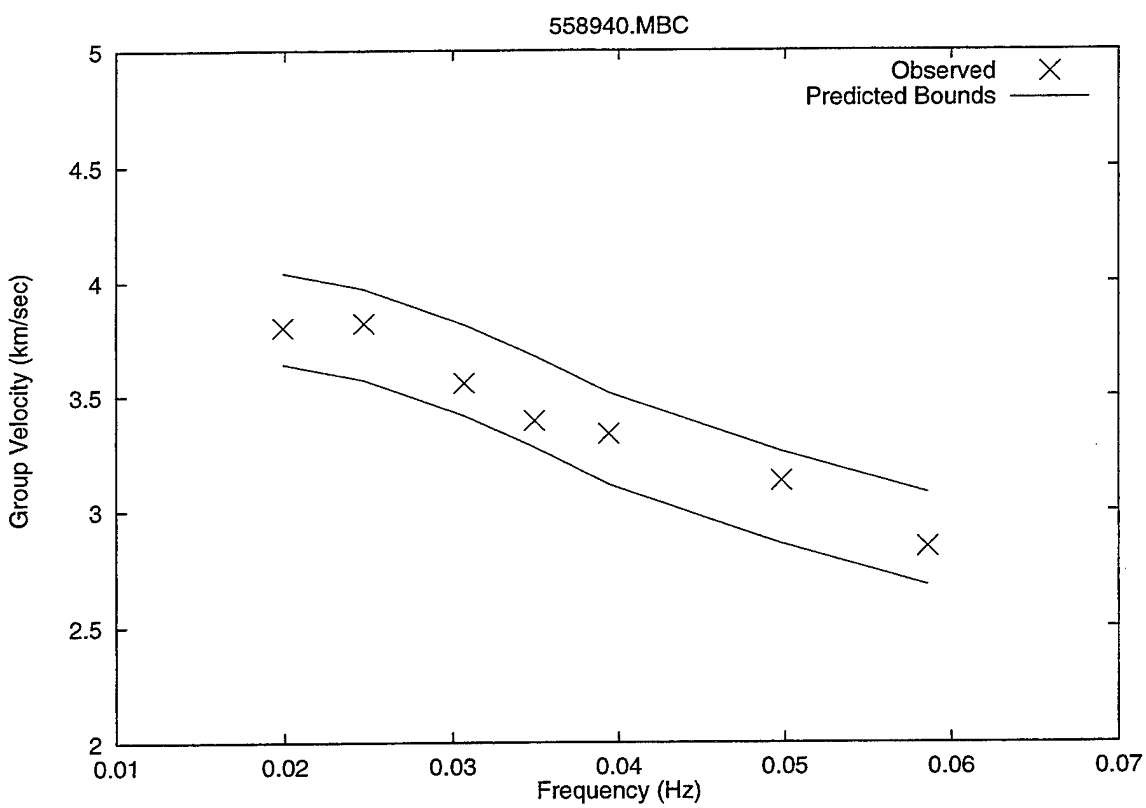

Figure 1. Predicted and measured group velocities from an earthquake recorded at MBC. Surface waves are identified in the automatic processing system by comparing measured dispersion curves with dispersion curves predicted by ray tracing along a great circle path through a regionalized earth model.

Currently, a surface wave is recorded in the database only if it passes both the dispersion and azimuth tests. Recent analysis of the procedure, however, has shown that the three-component azimuth test is unreliable because of a variety of problems with the horizontal instruments at the prototype IMS stations including polarization errors and high noise levels on the horizontal components. These problems cause a large fraction of good data to be rejected, so this test will probably be relaxed or removed in the near future.

Figures 2 and 3 show the azimuth residuals (the difference between measured and known azimuth) for seismograms passing the dispersion test, where the azimuth is estimated by array beaming and by three-component polarization filtering, respectively. Array beaming produces reliable and consistent results, however a large fraction of the three component azimuth estimates are found to be inconsistent with the known azimuth.

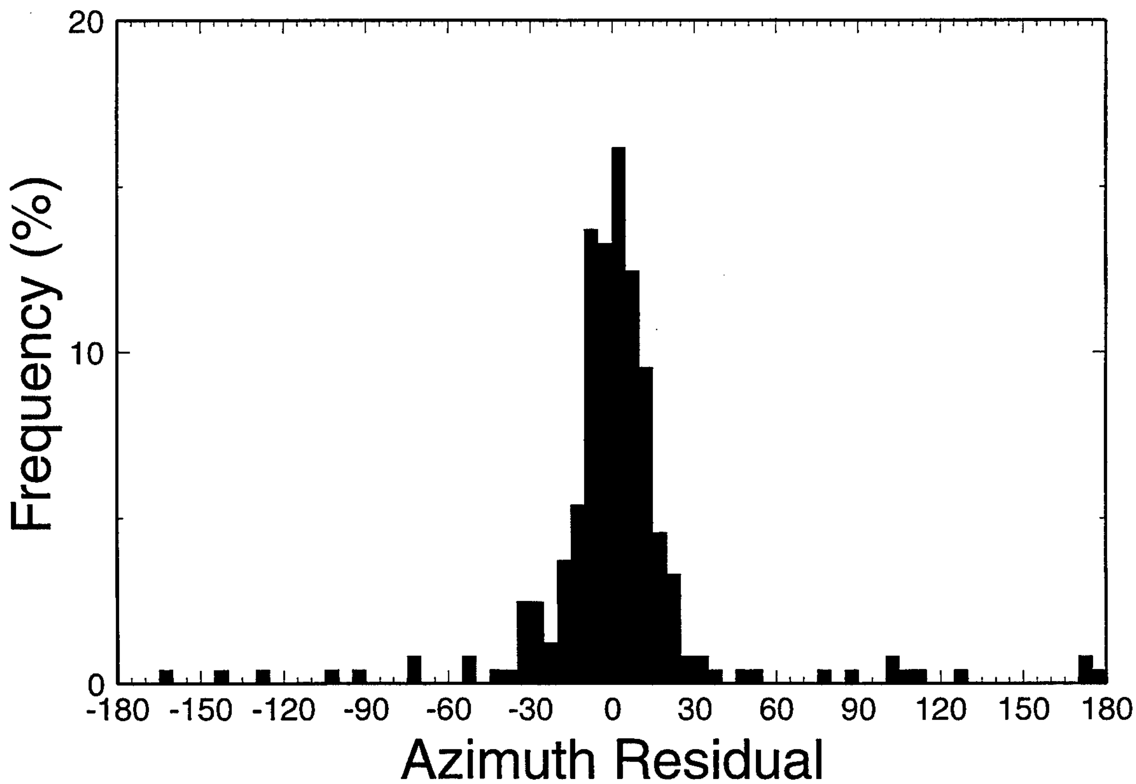

Figure 2. Histogram of azimuth residuals for 241 seismograms passing the dispersion test where the azimuth is estimated by array beaming.

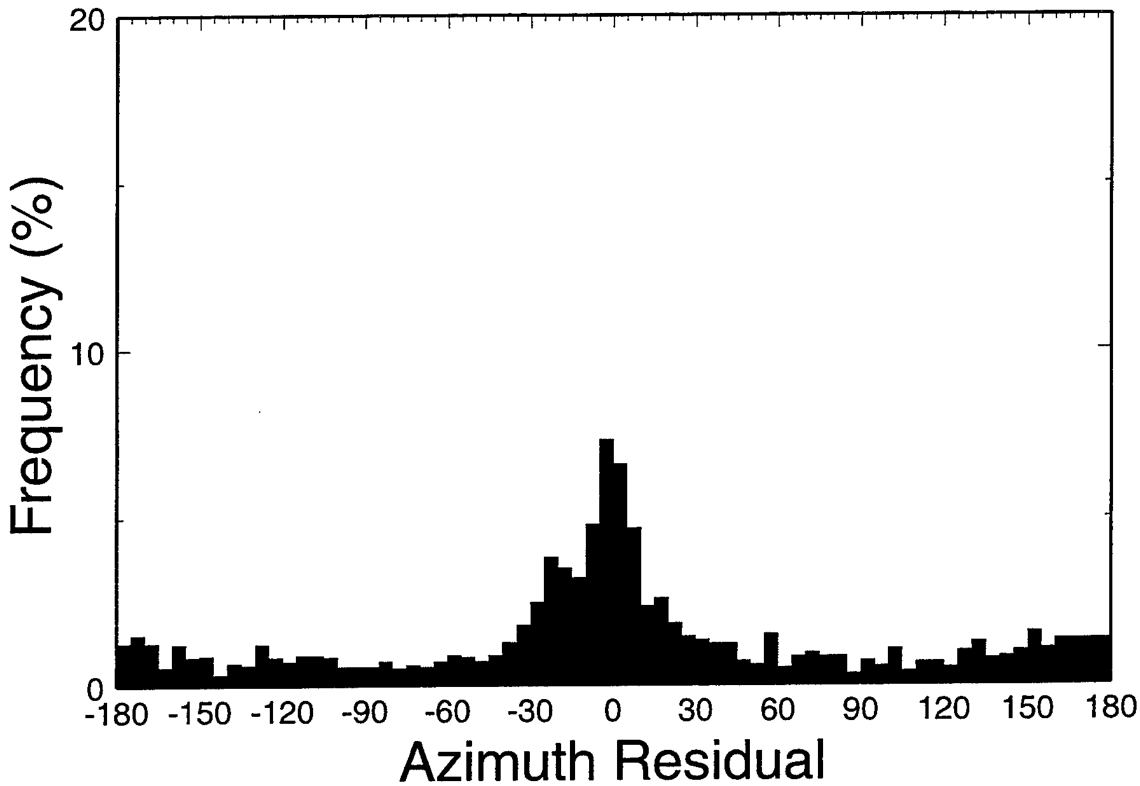

Figure 3. Histogram of azimuth residuals for 1763 seismograms passing the dispersion test where the azimuth is estimated by three-component polarization filtering.

An example of the problem with high noise levels on the horizontal components is shown in Figures 4 and 5 which show the seismograms and spectra recorded at station ZAL for the Chinese nuclear test of July 29, 1996. The Rayleigh arrival is clearly visible on the vertical component, but is masked by high long period noise levels on the horizontal components.

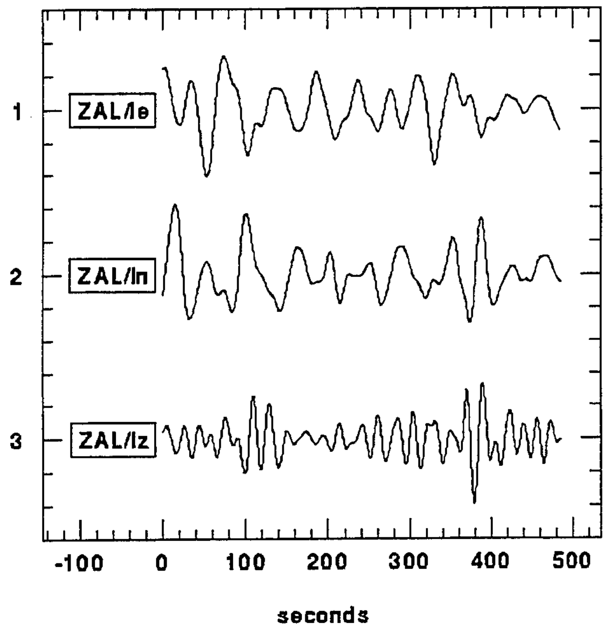

Figure 4. Seismograms showing high horizontal noise levels at station ZAL, 12.7 degrees from the Chinese nuclear test of July 28, 1996. This event had an M_s of 2.8 based on arrivals at ZAL and NRI.

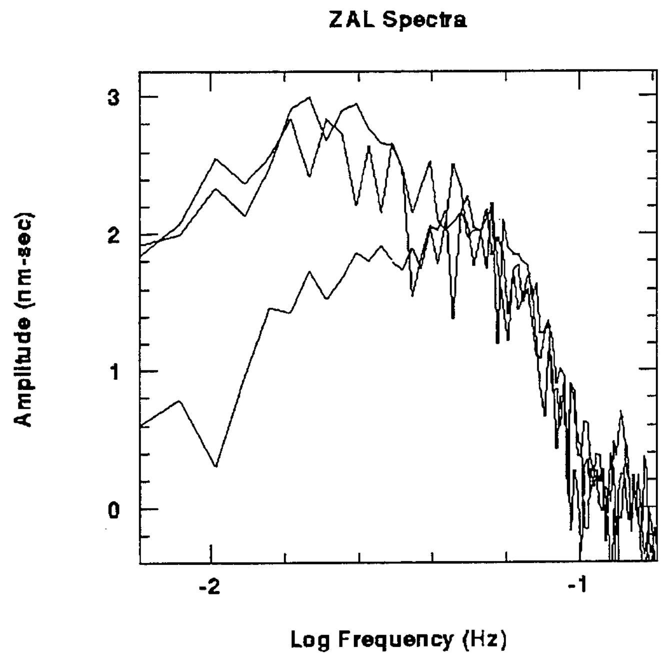

Figure 5. Spectra of seismograms shown in Figure 1. Noise levels on horizontal components are an order of magnitude larger than on the vertical component at low frequencies.

3.2 Phase-Matched Filtering and Moment Estimation

The phase-matched filtering module adds the following to the automatic processing:

1. A phase-matched filter is derived from ray tracing along a great circle path through a regionalized phase-velocity model consistent with the group velocity model described above.
2. The phase-matched filter is applied to the data to compress it to within a narrower time window, the data is windowed, and transformed back to the frequency domain. The result is a more accurate spectrum with higher signal to noise ratio.
3. The spectrum is divided by a theoretical explosion spectrum. The amplitude spectrum depends on the earth structure near the source and receiver and the attenuation along the path. Again these functions are derived from a regionalized earth model.
4. The spectral ratio is averaged over a frequency band, typically 0.02 to 0.05 Hz to give a single number, the scalar moment. For an explosion, the spectral ratio is flat as a function of frequency, and the resulting scalar moment will therefore be independent of frequency. This makes the scalar moment ideal as a regional magnitude, because it has the same value (in principle) whether measured at 10 seconds period at 1000 km, or at 25 seconds period at 10000 km. For an earthquake, the ratio depends on the

source mechanism and depth, and in general will not be flat, however the frequency dependence is reduced and the scalar moment can be measured at any frequency. The estimated scalar moment is related to the double couple moment of the earthquake through a distribution function which can be calculated theoretically. For this application, we are primarily interested in that part of the source that generates surface waves, which is the scalar moment, rather than the double couple moment which may be of more interest for earthquake research.

Figures 6 and 7 below show an example of waveform compression using phase-matched filtering. The original wave train had a duration of about 800 seconds and was compressed to within a time window of about 200 seconds. The compressed signal is offset from zero by about 50 seconds, indicating some residual error in the predicted phase velocity. The amount of compression can be improved and the offset reduced by improving the regionalized dispersion model. The ability of the current model to compress waveforms is quite remarkable given the relatively coarse 10 degree grid used for predicting phase velocities.

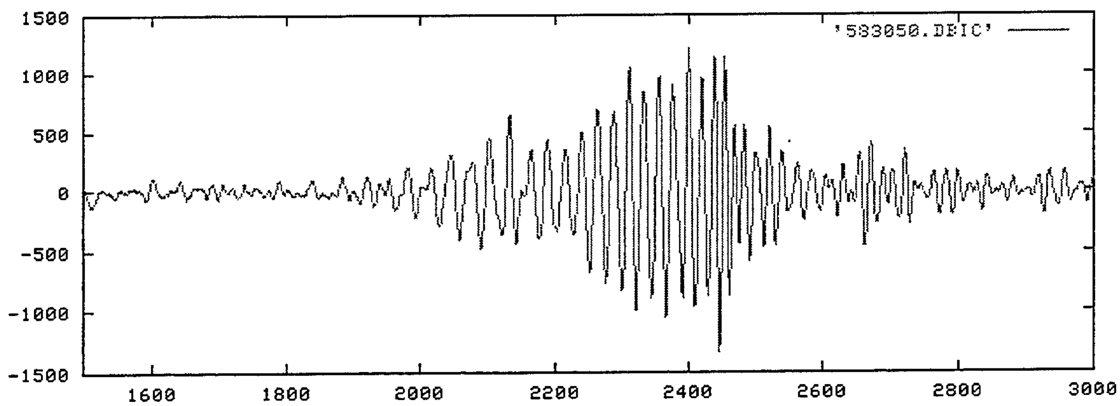

Figure 6.. Surface wave from earthquake recorded at station DBIC.

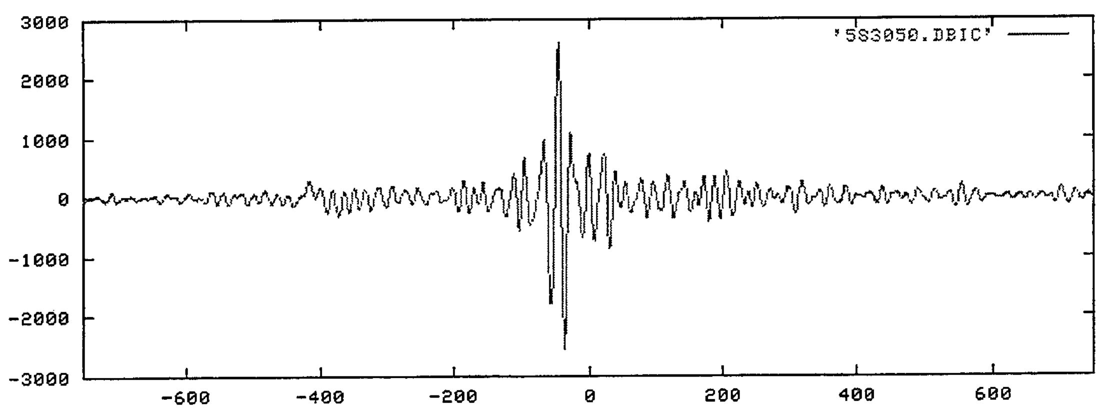

Figure 7. Surface wave from earthquake recorded at station DBIC after phase-matched filtering. The surface wave is compressed into a narrower time window allowing noise to be filtered out.

4. Regionalization of Surface Wave Properties

In order to perform the processing described above, we need to be able to determine the phase and group velocity and attenuation coefficients along any source to receiver path, and the surface wave amplitude factors at the source and receiver. We started with a set of group velocity dispersion curves from AFTAC and integrated these to obtain phase velocity dispersion curves. To date, we have used only generic models for the amplitude factors and attenuation coefficients, but expect to improve these in the next phase of this project. Note that although this procedure sounds more complicated than measuring M_s, M_s is really an equivalent measure using constant (average) values worldwide for amplitude factors, attenuation coefficients and dispersion.

The initial set of group velocity curves proved to be inadequate for accurately predicting dispersion curves, primarily because of a poor model for dispersion in subduction zones. We were able to improve the models through a combination of tomographic inversion of observed dispersion data and manual adjustment of the models. We ran Maxpmf on a data set from 264 events greater than m_b 4.5 recorded between October 9, 1995 and January 12, 1996, recovering approximately 2000 observed dispersion curves. We then examined the observed dispersion curves visually to remove inaccurate data points, and used these (approximately 1400 data points per frequency) to perform a tomographic inversion of world wide group velocity. To fill in some gaps in coverage and add some additional data points, we also included in the inversion 270 paths obtained during development of surface wave path corrections from a large data set of historical underground nuclear tests (Stevens, 1986). We used the Simultaneous Iterative Reconstruction Technique (SIRT; e.g. Olson, 1987) rather than the Algebraic Reconstruction Technique (ART; e.g. Censor, 1981) because the SIRT algorithm has the effect of averaging inconsistent data.

Figure 8 below shows the paths used for tomographic inversion of group velocity residuals. Because the tomographic inversion leads to a different dispersion curve for each grid cell, we did not use the tomographic results directly, but instead used them as a guide to improve the dispersion models. The final model, which uses 8 dispersion models on a 10 degree grid worldwide, predicts dispersion accurately for frequencies of 0.02 to 0.06 Hz. The group velocity model at a period of 50 seconds (0.02 Hz) is shown in Figure 9.

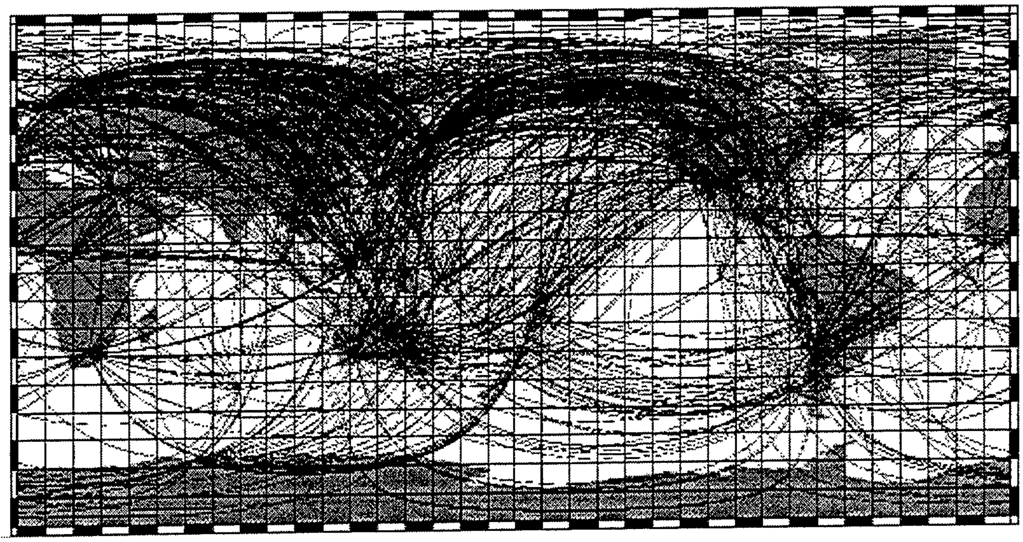

Figure 8. 2300 great circle paths used from tomographic inversion of group velocity residuals.

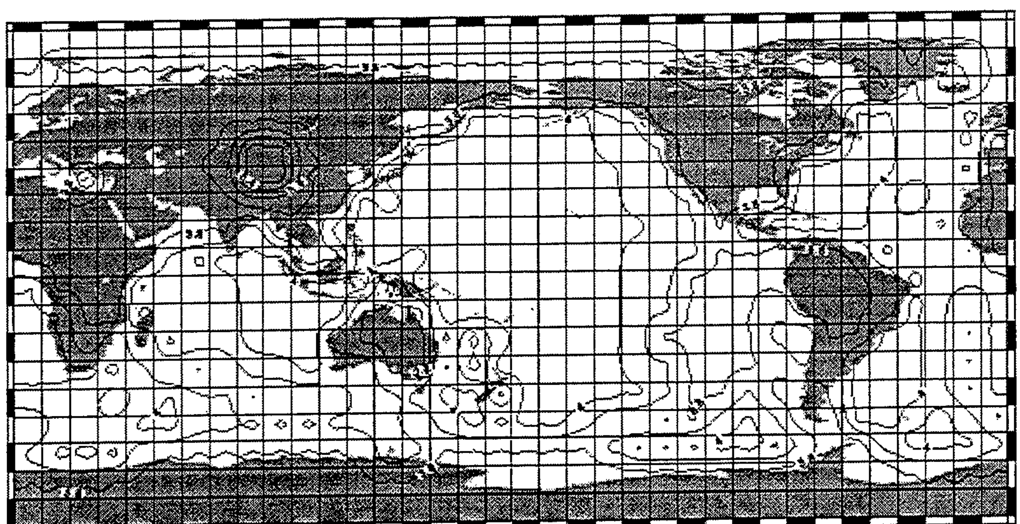

Figure 9. Contours of group velocities at 50 seconds period for the final 10x10 degree world wide model.

5. Maximum Likelihood Magnitude/Moment

There are two reasons for developing maximum likelihood magnitudes. The first is to determine station corrections to reduce the variance in network magnitudes. The second is to be able to use nondetections to get a better estimate of the magnitude by including a noise estimate in the magnitude calculation as an upper bound on the magnitude at that station. While in principle this is a straightforward procedure, there are practical problems that require careful attention to detail in order to make it work. Station corrections will vary according to the source region, so station corrections derived using a large volume of data from one area will be biased and possibly inaccurate for events in other areas. Similarly, if noise estimates are to be used as an upper bound on the magnitude, it must in fact be an upper bound on the magnitude. We have found that with

automatic processing it is very easy to inadvertently use low amplitude data from stations that are not operating properly and that this seriously distorts the estimated maximum likelihood magnitude. We tested automatic maximum likelihood processing on a set of about 4300 waveforms from 174 events recorded between January 13, 1996 and February 25, 1996.

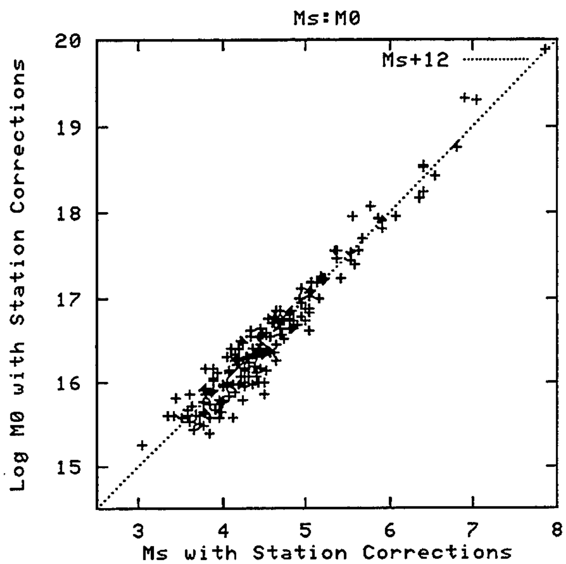

Figure 10. Station corrected network averaged Log Moment and M_s. Log Moment and M_s are similar measures of path corrected surface wave amplitude differing by approximately 12.

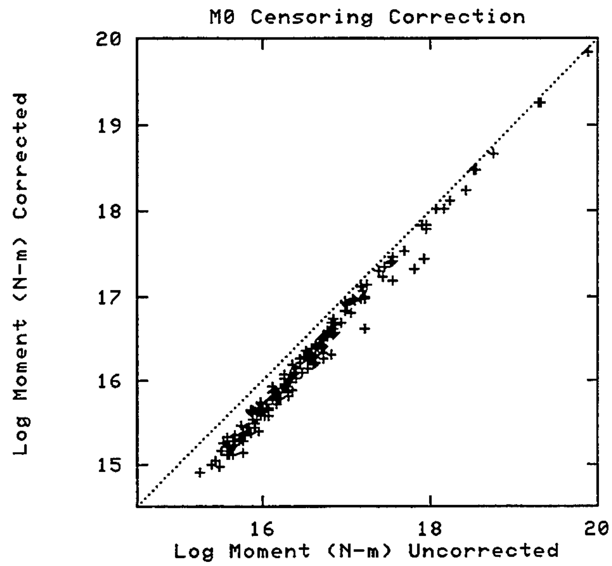

Figure 11. Log Moment with and without censoring correction. The censoring correction uses measured amplitudes of nondetections as noise estimates.

Figure 10 shows log M_0 plotted vs. M_s with maximum likelihood station corrections, but without censoring. M_s and log m_b differ by approximately 12.

Figure 11 shows the effect of the censoring correction. Here we have used the measured scalar moment as an upper bound on the moment for all data that did not satisfy the surface wave tests. The results show a gradual decrease in M_0 with the censoring correction as a function of decreasing M_0. This is to be expected since more noise estimates are included in the estimates for smaller events. However, the censoring correction shown here has too strong an effect. It does not completely go away even for the largest events. This is due primarily to problems with data quality and to the fact that the surface wave identification tests were designed to be conservative and fail to identify some data that contains surface wave signals. For example, some of the data is clipped, some contains small gaps, and some has high noise levels on the horizontal components. Any of these problems will cause the data to fail the polarization azimuth test and therefore identify signal as noise. Consequently additional quality control is needed, and as discussed previously, a less conservative detection test is desirable in order for the censoring correction to be meaningful.

6. Earthquake/Explosion Discrimination

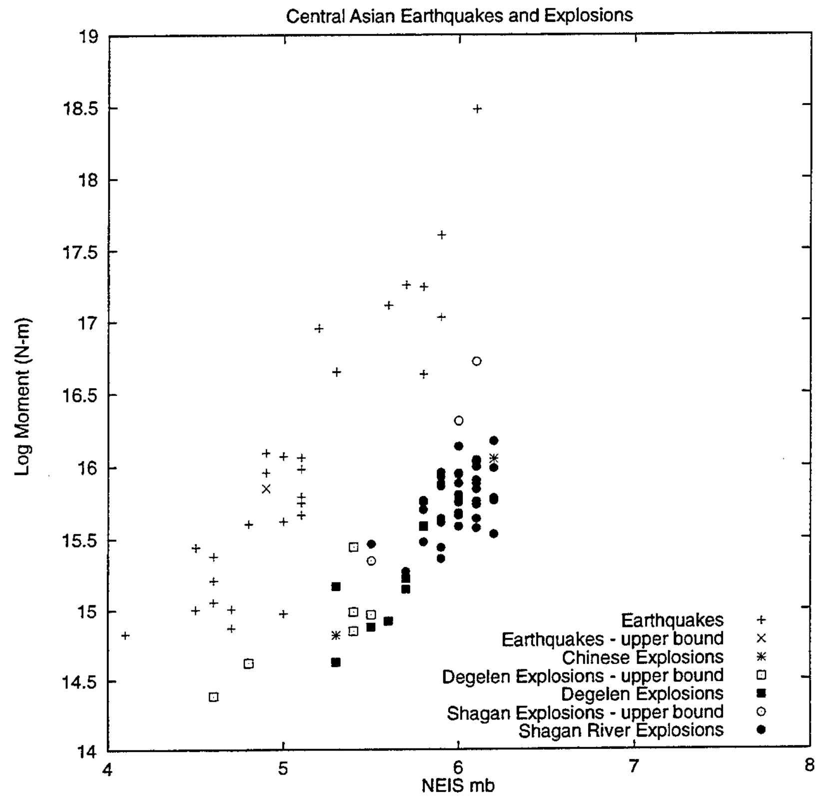

Figure 12. Plot of NEIS m_b vs. Log Moment for a data set of central Asian earthquakes and explosions. The open circles are an upper bound on log moment for events for which no surface wave data was visible either because of low signal/noise or an interfering event.

The most important function of surface wave magnitudes in a CTBT context is for discrimination. Figure 12 shows a plot of m_b vs. Log Moment for a data set of central Asian earthquakes and explosions (from Stevens and McLaughlin, 1988). Maximum likelihood moments were calculated for all events. For this data set, the data was carefully examined to remove any bad data. Data that did not visibly contain surface waves was treated as noise. Maximum likelihood magnitudes were calculated for all events, and an upper bound on the network magnitude was determined for all events with no useable surface wave data. This occurred for several small events, and for a couple of larger explosions where the surface waves were overwhelmed by surface waves from large earthquakes. The earthquakes and explosions clearly separate into distinct populations, and even the explosions with no surface wave data are clearly discriminated from the earthquake population for this data set. This is important, because surface waves are so much smaller for explosions than for earthquakes of a corresponding magnitude. Being able to use negative information substantially reduces the magnitude threshold for which explosions can be discriminated using the m_b:M_o (or m_b:M_s) discriminant.

Recent Chinese Underground Nuclear Tests					
Date	REB Origin ID	m_b	M_s	$Log(M_0)$	N arrivals
June 8, 1996	699783	5.69	3.95	15.68	12
July 29, 1996	754997	4.71	2.81	14.93	2

Figure 13 is a plot of IDC m_b vs. log Moment derived from prototype IDC data for the data set from early 1996 discussed in the last section, plus the Chinese underground nuclear tests of June 8, 1996 and July 29, 1996 (see table above). The Chinese tests are well separated from the earthquake population. Also shown on the plot is the line log $(M_o) = m_b+11$ which is an approximate discrimination line between the two populations.

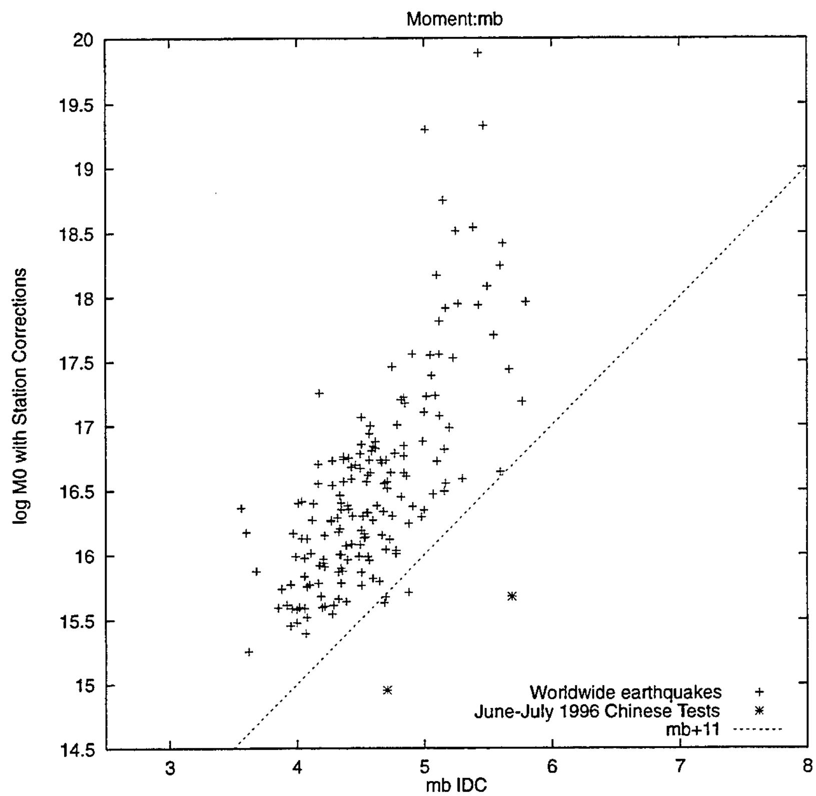

Figure 13. Log M_o vs m_b derived fromIDC data for early 996 plus the Chinese underground nuclear tests of June 8, 1996 and July 29, 1996.

7. Conclusions and Recommendations

1. Regionalization of phase and group velocities can be used to estimate phase and group velocities along any path. Even the relatively coarse 10 degree world wide grid used in this study is adequate for surface wave identification and phase-matched filtering. Further improvements are possible with a finer grid and improved earth models. Regionalization also appears to be practical for surface wave attenuation and source and receiver amplitude factors.
2. Automatic surface wave processing with a small amount of operator review works well for identification and measurement of surface waves and calculation of M_s and scalar moments.
3. Maximum likelihood magnitudes and moments with station corrections but without censoring can be easily calculated and automated.
4. Inclusion of censoring within maximum likelihood magnitudes requires a much higher level of quality control to ensure that the maximum likelihood magnitudes are not contaminated by poor quality data and improperly operating stations.
5. Scalar moments derived from surface waves appear to provide an effective discriminant when used in the same manner as the M_s:m_b discriminant. The advantage of scalar moments over M_s is that they can be regionalized and used at any distance range. With proper quality control, an upper bound can be determined for the moment of any event. The effect of these improvements is to reduce the magnitude threshold for which the surface waves can effectively discriminate earthquakes from underground nuclear explosions.

8. Future Plans

Work to date has set up the basic mechanism for performing optimized surface wave analysis, and implemented an operational system. What remains to be done is optimizing the system, improving quality control, and extending its range to shorter distances and higher frequency bands. The regionalization of dispersion done to date works reasonably well in the 0.02 to 0.06 Hz frequency band, but there is still room for improvement in this band, and more detail will be required for analyzing higher frequency surface waves at regional distances. In addition to dispersion, amplitudes (both path attenuation and source and receiver functions) need to be regionalized. Better quality control procedures need to be defined in order to make maximum likelihood magnitude and moment estimates. More regional data needs to be analyzed and the procedures tested for small events at closer distances using a higher frequency band. As in this study, making these improvements will require analysis of large data sets to ensure consistent results in an operational system.

9. Acknowledgements

We thank David Harkrider for many useful communications regarding earth structure modeling. We thank Walter Nagy of SAIC and Mark Woods of AFTAC for providing the ray tracing software and initial dispersion model. This work was sponsored by the Air Force Technical Applications Center and Phillips Laboratory under contract F19628-95-C-0110.

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